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TECHNICAL REPORT ARCSL-TR-77065

COMPUTER PROGRAM FOR REDUCTION AND PRESENTATION OF HIGH-PRESSURE CAPILLARY VISCOMETER DATA

by

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Frederick H. Gaskins

Research Division

September 1977

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
Chemical Systems Laboratory
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Newtonian liquids	Shear rate	Shear modulus
Non-Newtonian liquids	Digital computer	CALCOMP plotter
Univac 1108		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a description of a digital computer program for reducing and presenting data from the high-pressure capillary viscometer (HPCV). The HPCV is used to investigate the rheological behavior of viscoelastic fluids. A discussion of the theory and the viscometer's application is included. FORTRAN computer listings, sample input and output, and examples of the plotted rheological variables are further inclusions.

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SUMMARY

A digital computer program was developed to reduce significantly time and costs incurred in the reduction and presentation of the high-pressure capillary viscometer (HPCV) data. A savings of approximately 40 man-hours per experiment has already been achieved. Further benefits include greater accuracy and clearer and more precise graphics. Perhaps the most beneficial factor, however, is that erroneous data can be identified and corrected more rapidly than with the manual data reduction process. This is an important aspect because many test fluids deteriorate in storage and, if experiments are to be repeated, the test fluids may no longer be representative of the test series.

PREFACE

The work described in this report was performed under ILIR Task 1T161101A91A, In-House Laboratory Independent Research; Characterization of Liquids by Their Rheological Properties, and Task 1W662619A06501, Flame and Incendiary Agent Technology. The work was begun in April 1976 and completed in January 1977.

The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or software. This report may not be cited for purposes of advertisement.

Acknowledgments

The authors acknowledge the assistance of Edmund M. Wilbur and Charles M. Lawson, fellow workers in the Physics Branch of Research Division.

CONTENTS

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COMPUTER PROGRAM FOR REDUCTION AND PRESENTATION OF HIGH-PRESSURE CAPILLARY VISCOMETER DATA

I. INTRODUCTION.

This report describes a digital computer program for reduction of rheological data acquired from the high-pressure capillary viscometer (HPCV) and presentation of that reduced data by preparation of graphs of the prime rheological parameters.

The program is written for the Edgewood Arsenal Univac 1108 computer in FORTRAN V language. Double-logarithmic plots of the reduced data are drawn by the California Computer Products CALCOMP plotter.

II. THEORY AND APPLICATIONS.[1]

The HPCV is used in the investigation of the rheological behavior of viscoelastic fluids. It is designed to permit calculation of rheological variables (refer to glossary) from geometric parameters combined with pressure, mass flow, and time data. The HPCV provides a steady-state unidirectional laminar flow of the test fluid by generating a constant stress at controlled pressure levels.

The nucleus of the HPCV is the removable precision-bore capillary tube which is inserted between two 100-ml test fluid reservoirs. The capillary tube and reservoir assembly, including lead-in lines and connecting tubes, are constructed of stainless steel. To insure complete temperature control of the test sample, the fluid reservoir assembly is placed into a temperature bath. In operation, pressurized gas, controlled by a network of valves and regulators and monitored by a bank of precision gages, forces test fluid from one reservoir through the capillary tube to the second reservoir. This action forces gas from the second reservoir to impinge on a low-viscosity fluid, such as n-hexane, driving it through a burette at the same flow rate being experienced by the test fluid.

Volumetric flow-time relationships are determined from the burette readings. Pressure gradients of 10^{-3} to 10^{3} psig can be applied with the HPCV resulting in an operating shear rate range of 10^{-3} to 10^{6} seconds^{-1}.

Table 1 presents a listing of the capillary tube sets and their dimensions.

Two basic experiments are performed with the HPCV. The short-series experiment involves volume flow-rate measurements performed with the longest capillary tube of each group. These data permit shear stress, shear rate, and apparent viscosity to be calculated.

The calculated data can then be used to generate shear stress versus shear rate and viscosity versus shear rate plots. These generated plots are known as the basic flow curves and are adequate to describe fully the rheological behavior of Newtonian or inelastic non-Newtonian liquids.

---

[1] Gaskins, Frederick H. EATR 4472. Characterization of Thickened Aluminum Alkyl Fuels. II. Steady-State Flow Properties of Concentrated Solutions of Polyisobutylene in Triethylaluminum. Janaury 1971. UNCLASSIFIED Report.

Table 1. Capillary Viscometer Parameters

Group	Tube No.	Length		Nominal diameter		R	L/R
		in	cm	in	cm	cm	
A	11	2.0020	5.0851	0.205	0.52	0.26	19.6
B	7	1.9914	5.0582	0.127	0.322	0.161	31.4
	10	0.4485	1.1392	0.127	0.322	0.161	7.08
C	5	1.9985	5.0759	0.0646	0.164	0.0820	61.9
	8	0.6502	1.6515	0.0646	0.164	0.0820	20.1
	15	0.1839	0.4671	0.0646	0.164	0.0820	5.70
D	9	2.0021	5.0353	0.0244	0.0619	0.0310	164.0
	6	0.5960	1.5138	0.0244	0.0619	0.0310	48.8
	14	0.1534	0.3896	0.0244	0.0619	0.0310	12.6
E	3	1.5082	3.8308	0.0146	0.0370	0.0185	207.0
	4	0.3318	0.8428	0.0146	0.0370	0.0185	45.6
	13	0.0859	0.2182	0.0146	0.0370	0.0185	11.8
F.	1	1.0155	2.5794	0.00807	0.0205	0.0103	250.0
	2	0.2346	0.5959	0.00807	0.0205	0.0103	57.9
	12	0.317	0.0805	0.00807	0.0205	0.0103	7.82

More information is needed to describe the flow of high-polymer or other viscoelastic solutions. This is accomplished by the use of all the capillary tubes in a long-series experiment. These additional data permit calculation of recoverable shear, shear modulus, relaxation time, and normal stress, parameters needed to describe the fluid's elasticity.

The HPCV is limited by the shear-rate range in which it can operate. For lower shear rates, less than 10^{-3} seconds^{-1}, the rotational viscometer or the Weissenberg rheogoniometer is used to acquire needed data. The Weissenberg rheogoniometer also is more accurate since it measures elasticity directly as compared to the HPCV where elasticity is a computed function of physical and rheological factors.

III. COMPUTER-PROGRAM DESCRIPTION.

The computer program matches the basic experiments performed with the HPCV; i.e., the first phase provides data reduction and graphic interpretation for the short-series experiments and the second phase provides data reduction and graphic interpretation for the long-series experiments.

A. Short-Series Phase.

Appendix A contains the flow chart and the program listing.

The first section establishes arrays and procedures for data input. Volume-time data, i.e., the flow rates through the capillary tubes, for each pressure level are fed into the computer. Appendix A contains sample input. A slope and y-intercept are calculated at each pressure level from the volume-time coordinates.

Values for shear rate and shear stress are then calculated by using capillary tube dimensions and the following rheological relationships:

$$\dot{\gamma}_m = 4S/\pi r^3 \quad (1)$$

$$\sigma = r\Delta P/2\ell \quad (2)$$

where

$\dot{\gamma}_m$ = shear rate, sec^{-1}

r = capillary tube radius, cm

S = slope or volumetric flow rate, cc/sec

σ = shear stress, dynes/cm^2

ΔP = pressure, dynes/cm^2

ℓ = capillary tube length, cm

The apparent viscosity at each pressure level is calculated as a function of the shear stress divided by the shear rate.

The reduced data are printed in tabular form. Appendix A contains sample output.

Two double-logarithmic plots of the reduced data are drawn by the CALCOMP plotter. One plot is a graph of shear rate versus shear stress; the other plot presents apparent viscosity versus shear rate. On each graph, a best fit curve is drawn through the data points. This curve is computed using E. Wilbur's program for fitting a polynomial equation as high as the sixth degree to the data.

Appendix A contains a sample plot of the basic flow curves (figures A-1 and A-2).

B. Long-Series Phase.

Appendix B contains a flow chart and the program listing.

The input is basically the same as for a short series, except that an extra card is used to read in the number of groups of capillary tubes and their designations. Appendix B contains sample input. The same basic calculations are performed for shear rate, shear stress, and viscosity, and a double logarithmic plot of shear rate versus shear stress is drawn. A curve is plotted for each capillary used. A sample plot of these basic intermediate curves for one capillary group is contained in appendix B (figure B-1).

Values for shear rate and shear stress selected for this intermediate plot are then used to predict certain viscoelastic properties of the material studied. Furthermore, by examining the general slope of these curves and recognizing those points that deviate from the norm, erroneous data are located and immediately deleted.

For each group of capillary tubes, six isoshear rates are selected. For each selected shear rate, a corresponding shear stress, the total shear stress (refer to glossary), is calculated. The total shear stress then permits the applied pressure to be computed:

$$\sigma_t = (\dot{\gamma}_{ms} - BT)/S_t \qquad (3)$$

$$\Delta P = (2\ell/r)\sigma_t \qquad (4)$$

where

σ_t = total shear stress, dynes/cm^2

$\dot{\gamma}_{ms}$ = selected shear rate, sec^{-1}

BT = y-intercept of shear rate versus shear stress curve

S_t = slope of shear rate versus shear stress curve

ΔP = applied pressure, dynes/cm^2

ℓ = length of capillary tube, cm

r = radius of capillary tube, cm

Analyzing the applied pressure versus ℓ/r ratios of the capillary tubes by groups, values for corrected shear stress and recoverable shear are computed. The corrected shear stress equals the slope of the applied pressure versus the ℓ/r ratio curve divided by two. Recoverable shear equals the X-axis intercept multiplied by a negative two. More detailed explanations are contained in the glossary and table 2.

Table 2. Matrix for the Capillary Experiment*

Function	X-intercept	Y-intercept	Slope
$\sigma_t = f(r/\ell)$	$(r/\ell)_{\sigma_t \to o} = -2/\gamma_R$	$(\sigma_t)_{\ell \to \infty} = \sigma_c$	$\sigma_c(\gamma_R/2)$
$P_t = f(\ell/r)$	$(\ell/r)_{P_t \to o} = -\gamma_R/2$	$(P_t)_{\ell \to o} = \sigma_c \cdot \gamma_R$	$2\sigma_c$

*According to Philippoff and Gaskins.[2] Note that the original matrix in the reference (page 269) has been modified by deletion of the Couette correction, "n". This simplification is based on the rationale that "n", which is an entrance correction, is constant for various capillary tubes with the same radius, and the computer program sequence presented in this report evaluates elasticity from data for groups of tubes of the same radius at constant shear rates.

Additional rheological parameters, including apparent and effective viscosity, shear modulus, relaxation time, and normal stress, are calculated as follows:

$$\eta_a = \sigma_c/\dot{\gamma}_{ms} \tag{5}$$

$$\eta_e = \eta_a(1 + \gamma_R) \tag{6}$$

$$G = \sigma_c/\gamma_R \tag{7}$$

$$t = \gamma_R/\dot{\gamma}_{ms} \tag{8}$$

$$N_1 = \sigma_c \cdot \gamma_R \tag{9}$$

where

η_a = apparent viscosity, poise

η_e = effective viscosity, poise (empirical relationship)

σ_c = corrected shear stress, dynes/cm^2

---

[2]Philippoff, W., and Gaskins, F. H. The Capillary Experiment in Rheology. Transactions of the Society of Rheology *II*, 263-284 (1958).

$\dot{\gamma}_{ms}$ = selected shear rate, sec^{-1}

G = shear modulus, $dynes/cm^2$

γ_R = recoverable shear, dimensionless

t = relaxation time, seconds

N_1 = normal stress, $dynes/cm^2$

Five double logarithmic plots of the computed viscoelastic properties are drawn.

Plot one, the flow curve, is selected shear rate versus corrected shear stress. The inverse slope at any point is the apparent viscosity.

Plot two, the viscosity-rate curve, shows the apparent viscosity versus the selected shear rate.

Plot three, the deformation curve, is recoverable shear versus the corrected shear stress. The inverse slope at any point is the shear modulus.

Plot four, the deformation-rate curve, shows recoverable shear versus selected shear rates. The slope at any point equals the relaxation time.

Plot five, the normal stress-rate curve, is the normal stress versus the selected rates.

Appendix B also contains samples of these five plots for a viscoelastic fluid combining all the capillary groups (figure B-2).

IV. OPERATING INSTRUCTIONS.

A deck of Hollerith cards containing all of the FORTRAN V statements and control cards is necessary for operation of the program and assigning plot tapes. The Univac 1108 uses the EXEC VIII control language. The number and format of control cards may vary somewhat in different computer installations; therefore, they are not considered in this report. Consult your computer information directorate for appropriate control cards.

V. CONCLUSIONS.

This computer program reduces significantly the time and costs for data reduction and evaluation for experiments conducted with the HPCV. Sixteen man-hours are saved for each short-series experiment and approximately 40 man-hours are saved for each long-series experiment. A step-to-step procedure for manual data reduction is presented in appendix C.

Additional benefits are greater accuracy and minimization of errors inherent in manual data reduction. The curve-fitting technique further reduces errors or distortions caused by visual evaluation and manual attempts to fit curves to data points. The program provides an equation of

the best-fit curve which permits further information to be predicted accurately. Finally, clearer and more precise graphics, ready-made for inclusion in reports, are produced.

Probably the most important benefit is that erroneous data can be identified rapidly and a test-series experiment can be repeated immediately. This is an important aspect because many test fluids deteriorate in storage and are not representative of the test series if repeat experiments are delayed as was usually the case when manual data reduction was necessary.

SELECTED REFERENCES

1. Programming CALCOMP Pen Plotters. California Computer Productions, Inc. September 1969.

2. CALCOMP Graphics Functional Software, USA FORTRAN/Scientific. California Computer Products, Inc. July 1969.

3. Wilbur, Edmund. Least Squares Program for Fitting Polynomial Curves. To be published as an ARCSL technical report. 1977.

4. The Weissenberg Rheogoniometer, Instruction Manual for Model R.18. Sangamo Controls Limited. Sussex, England.

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GLOSSARY

1. Shear rate, $\dot{\gamma}_m$, sec^{-1}: The deformation rate developed across the stress field; also, the irreversible shear flow of the fluid.

2. Shear stress, σ, dynes/cm^2: The tangential force per unit area exerted on the fluid causing deformation, orientation, or flow.

   a. Total shear stress, σ_t: Calculated value based on the tube geometry and the total pressure gradient which includes the pressure utilized in reversible elastic deformation (see equation 3 in text).

   b. Corrected shear stress, σ_c: Reduced value based only on portion of pressure utilized in irreversible viscous flow.

3. Recoverable shear, γ_R, dimensionless: The reversible elastic shear strain developed in the fluid under shear that may be recovered in real time after cessation of flow or removal of stress.

4. Viscosity, $\eta = \sigma/\dot{\gamma}_m$, in poise or dynes-sec/$cm^2$: The resistance to flow offered by the fluid under shear.

   a. Apparent viscosity, η_a: Variable function of shear rate.

   b. Effective viscosity, η_e, dynes/cm^2: An empirical term relating a fluid's viscous and elastic components – $\eta_e = \eta_a(1 + \gamma_R)$. Note also relaxation time definition.

5. Normal stress, $N_1 = \sigma \cdot \gamma_R$, dynes/$cm^2$: The first normal stress functions; force perpendicular to direction of flow.

6. Shear modulus, $G = \sigma/\gamma_R$, dynes/cm^2: The modulus of elasticity measured in shear (equivalent to Hooke's law).

7. Relaxation time, $t = \eta/G = \gamma_R/\dot{\gamma}_m$, sec: The time required for a strained or sheared material to recover after stress removal (also called retardation time).

8. Newtonian fluid: Viscosity is a constant, independent of shear rate.

9. Non-Newtonian fluid: Viscosity is a variable function of shear rate.

10. Viscoelastic fluid: Material under shear demonstrates viscous response (irreversible flow) and elastic response (reversible storage).

11. Inelastic fluid: Material under shear demonstrates no elastic response.

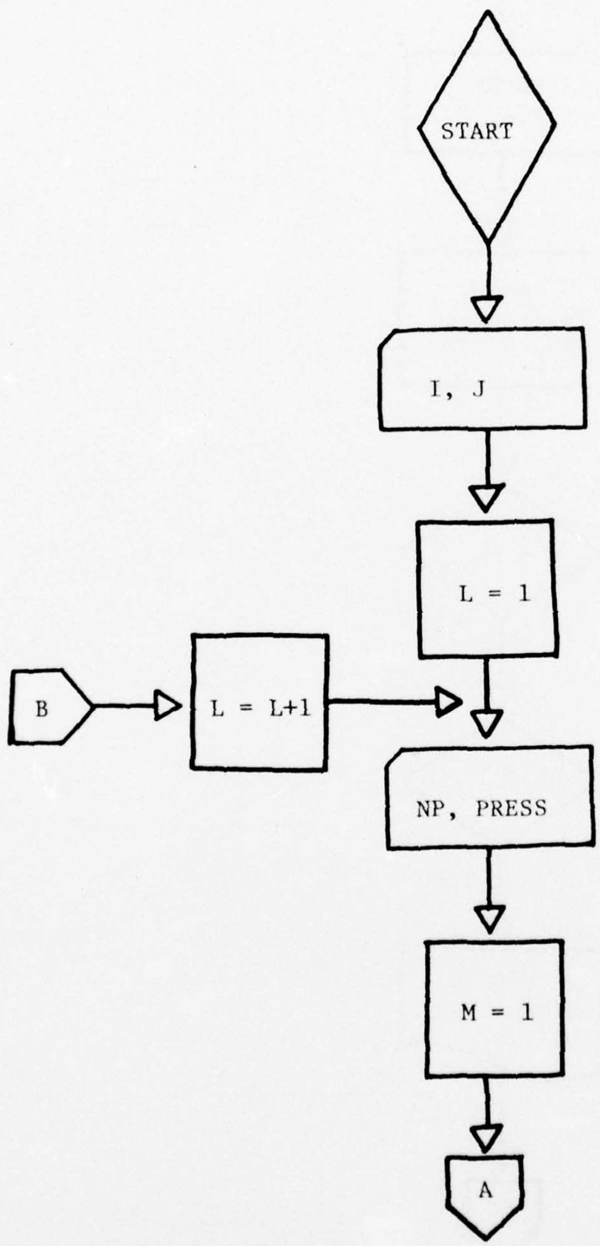
PROGRAM VARIABLES

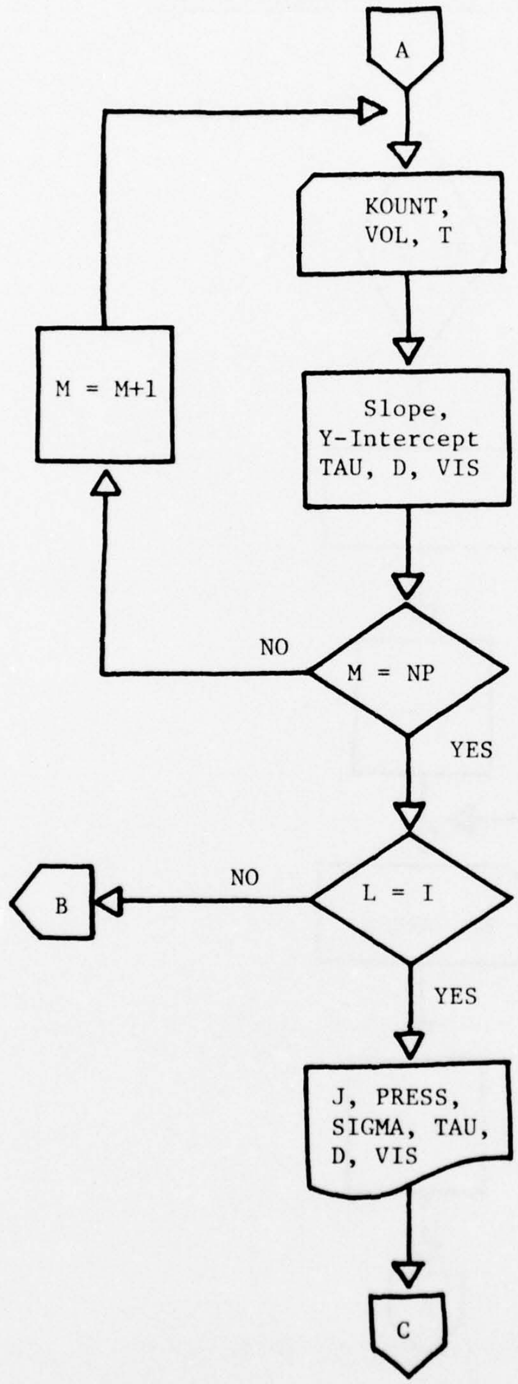
VARIABLE	DESCRIPTION
1. GROUP	A, B, C, D, E, F
2. TL	Tube lengths
3. TR	Tube radii
4. TK	Constant ratio $(2\,\ell/r)$
5. DK	Constant $\left(\frac{4}{\pi r^3}\right)$
6. IG	Number of groups
7. IGN	Group number
8. IT or I	Number of tubes
9. ITUB or J	Tube number
10. NP	Number of pressure readings
11. PRESS	Pressure readings
12. KOUNT	Number of volume readings
13. VOL	Volume levels recorded
14. T	Time
15. SIGMA	Slope of VOL versus T readings
16. B	Y-intercept of VOL versus T data
17. TAU	Shear stress
18. D	Shear rate
19. VIS	Viscosity
20. DM	Maximum D for each tube
21. DMX	Minimum maximum D for each group
22. DN	Minimum D for each tube
23. DMN	Maximum minimum D for each group
24. R	Maximum D minus minimum D
25. PM	Midpoint of R

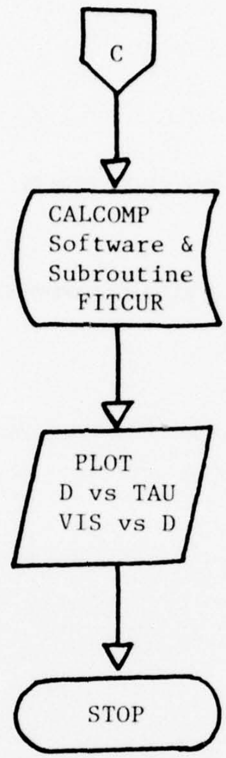
VARIABLE	DESCRIPTION
26. SD	Selected D
27. SIGMAT	Slope of D versus TAU data
28. TAUT	Shear stress for each SD
29. DP	Pressure for each TAUT
30. TKS	TK/2
31. TAUC	Slope DP versus ℓ/r data
32. RSC	Recoverable shear
33. VISA	Apparent viscosity
34. G	Shear modulus
35. RT	Relaxation time
36. BC	Y-intercept of DP versus TKS
37. NN	Pressure number (NP)
38. BT	Y-intercept of D versus TAU
39. NM	Tube number (IT)
40. PN	Normal stress
41. D2 or DS	D values for plot
42. VIS2 or VISS	VIS values for plot
43. TAU2 or TAUS	TAU values for plot
44. SD2	SD values for plot
45. TAUC2	TAUC values for plot
46. VISA2	VISA values for plot
47. RSC1	RSC values for plot
48. PN2	PN values for plot
49. XPAGE	X-values for plot
50. YPAGE	Y-values for plot
51. FPR	Predicted Y-axis values
52. EV	Effective viscosity

APPENDIX A

FLOW CHART FOR SHORT-SERIES PHASE




A
KOUNT,
VOL, T
Slope,
Y-Intercept
TAU, D, VIS
M = M+1
NO
M = NP
YES
NO
B
L = I
YES
J, PRESS,
SIGMA, TAU,
D, VIS
C


C
CALCOMP Software & Subroutine FITCUR
PLOT
D vs TAU
VIS vs D
STOP

```
TNG,5316J065212,RESEAR,2,100

LARRYW.
6-02/04-12:37

RRYW.

RYW.

ISCAP,.VISCAP
2/04/77-12:37:42 (,0)
```

SAMPLE LISTING FOR SHORT SERIES

```
OGRAM

 USED: CODE(1) 000725; DATA(0) 015534; BLANK COMMON(2) 000000


L REFERENCES (BLOCK, NAME)

 PLOTS
 PLOT
 FACTOR
 LGAXS
 LGLIN
 SYMBOL
 FITCUR
 SMOOT
 NINTR$
 NRDU$
 NIO1$
 NIO2$
 NWDU$
 ALOG10
 NSTOP$


 ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

 015361 1F         0000   015364 100F      0000   015416 104F      0001   000013 1
 000076 142G       0001   000113 156G      0000   015362 2F        0001   000422 2
 000476 202L       0001   000511 203L      0001   000515 204L      0001   000223 2
 000243 221G       0000   015363 3F        0001   000622 300L      0001   000664 3
 000712 303L       0001   000716 304L      0001   000046 5L        0001   000207 5
 007607 B          0000 R 011413 D         0000 R 000055 DK        0000 R 013524 D
 015336 I          0000 I 015360 ID        0000 I 000074 J         0000 I 015341 J
 015344 KOUNT      0000 I 015340 L         0000 I 015343 M         0000 I 015345 N
 015357 NM         0000 I 013217 NN        0000 I 015342 NP        0000 I 015356 N
 006705 SIGMA      0000 R 015346 ST        0000 R 015347 STS       0000 R 015352 S
 015351 SVS        0000 R 003751 T         0000 R 010511 TAU       0000 R 013236 T
 000000 TL         0000 R 015354 TM        0000 R 000017 TR        0000 R 015355 T
 014012 VISS       0000 R 001015 VOL       0000 R 014566 XPAGE     0000 R 015052 Y


 1*          DIMENSION TL(15),TR(15),TK(15),DK(15),J(15),PRESS(15,30),VOL(30,50
 2*         C),T(30,50),SIGMA(15,30),B(15,30),TAU(15,30),D(15,30),VIS(15,30),NN
```

```
      C(15),TAUS(182),DS(182),VISS(182),EPR(182)
       DIMENSION XPAGE(180),YPAGE(180)
       DATA TL/2.5794,0.5959,3.8308,0.8428,5.0759,1.5138,5.0582,1.6515,5.
      C0853,1.1392,5.0851,0.0805,0.2182,0.3896,0.4671/
       DATA TR/0.0103,0.0103,0.0185,0.0185,0.0820,0.0310,0.1610,0.0820,0.
      C0310,0.1610,0.2600,0.0103,0.0185,0.0310,0.0820/
       DATA TK/138.,597.,167.,751.,554.,702.,1095.,1710.,209.5,4870.,1760
      C.,4410.,2920.,2740.,6050./
       DATA DK/1.17E+6,1.17E+6,2.01E+5,2.01E+5,2.3E+3,4.26E+4,3.05E+2,2.3
      CE+3,4.26E+4,3.05E+2,7.22E+1,1.17E+6,2.01E+5,4.26E+4,2.3E+3/
       READ(5,1) I,(J(K),K=1,I)
     1 FORMAT(  )
       L=1
     6 JK=J(L)
       READ(5,2) NP,(PRESS(JK,K),K=1,NP)
     2 FORMAT(  )
       M=1
     5 READ(5,3) KOUNT,(VOL(M,N),T(M,N),N=1,KOUNT)
     3 FORMAT(  )
    30 ST=0.
       STS=0.
       SV=0.
       SVS=0.
       STV=0.
       DO 10 NK=1,KOUNT
       ST=ST+T(M,NK)
       STS=STS+T(M,NK)**2.
       SV=SV+VOL(M,NK)
       SVS=SVS+VOL(M,NK)**2.
       STV=STV+T(M,NK)*VOL(M,NK)
    10 CONTINUE
       SIGMA(L,M)=(STV-((ST*SV)/KOUNT))/(STS-(ST**2.)/KOUNT)
       TM=ST/KOUNT
       TV=SV/KOUNT
       B(L,M)=TV-SIGMA(L,M)*TM
       TAU(L,M)=PRESS(JK,M)*TK(JK)
       D(L,M)=SIGMA(L,M)*DK(JK)
       VIS(L,M)=TAU(L,M)/D(L,M)
       IF(M.EQ.NP) GO TO 22
       M=M+1
       GO TO 5
    22 NN(JK)=NP
       IF(L.EQ.I) GO TO 50
       L=L+1
       GO TO 6
    50 WRITE(6,100)
   100 FORMAT('1',' CAPILLARY   PRESSURE   SLOPE   SHEAR STRESS   SHEAR
      CRATE   VISCOSITY'/'  NUMBER        PSI       CC/SEC     DYNES/CM2
      C   1/SEC         POISE')
       NXY=1
       DO 102 K=1,I
       JK=J(K)
       NP=NN(JK)
       DO 103 NM=1,NP
       WRITE(6,104) J(K),PRESS(JK,NM),SIGMA(K,NM),TAU(K,NM),D(K,NM),VIS(K
      C,NM)
   104 FORMAT(6X,I2,6X,F7.2,4X,F5.3,4X,F9.2,6X,F9.2,3X,F9.4)
```

```
            TAUS(NXY)=TAU(K,NM)
            DS(NXY)=D(K,NM)
            VISS(NXY)=VIS(K,NM)
            NXY=NXY+1
      103 CONTINUE
      102 CONTINUE
            NXY=NXY-1
      500 CALL PLOTS(ID,ID,8)
            CALL PLOT(0.0,-36.0,-3)
            CALL PLOT(0.0,2.0,-3)
            CALL FACTOR(0.75)
            TAUS(NXY+1)=1.0
            TAUS(NXY+2)=.50
            DS(NXY+1)=1.0
            DS(NXY+2)=.50
            CALL  LGAXS(0.0,0.0,29HSHEAR STRESS-DYNES/CM-SQUARED,-29,12.0,0.0,
           C1.0,.50)
            CALL  LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,29,12.0,90.0,
           C1.0,.50)
            CALL LGLIN(TAUS,DS,NXY,1,-1,11,0)
            CALL SYMBOL(3.0,12.0,.21,27HSHEAR RATE VS. SHEAR STRESS,0.0,27)
            CALL FITCUR(TAUS,DS,NXY,FPR)
            FPR(NXY+1)=1.0
            FPR(NXY+2)=.50
            CALL LGLIN(TAUS,FPR,NXY,1,-1,2,0)
            N=1
      200 XPAGE(N)=(ALOG10(TAUS(N)))/TAUS(NXY+2)
            YPAGE(N)=(ALOG10(FPR(N)))/DS(NXY+2)
            IF(N.EQ.1) GO TO 201
            IF(N.EQ.NXY) GO TO 202
            CALL SMOOT(XPAGE(N),YPAGE(N),-2)
            GO TO 203
      201 CALL SMOOT(XPAGE(N),YPAGE(N),0)
            GO TO 203
      202 CALL SMOOT(XPAGE(N),YPAGE(N),-24)
            GO TO 204
      203 N=N+1
            GO TO 200
      204 CALL PLOT(0.0,16.0,-3)
            VISS(NXY+1)=.01
            VISS(NXY+2)=.50
            CALL  LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,-29,12.0,0.0,
           C1.0,.50)
            CALL  LGAXS(0.0,0.0,15HVISCOSITY-POISE,15,12.0,90.0,.01,.50)
            CALL LGLIN(DS,VISS,NXY,1,-1,11,0)
            CALL SYMBOL(3.0,12.0,.21,24HVISCOSITY VS. SHEAR RATE,0.0,24)
            CALL FITCUR(DS,VISS,NXY,FPR)
            FPR(NXY+1)=.01
            FPR(NXY+2)=.50
            CALL LGLIN(DS,FPR,NXY,1,-1,2,0)
            N=1
      300 XPAGE(N)=(ALOG10(DS(N)))/DS(NXY+2)
            YPAGE(N)=((ALOG10(FPR(N)))/VISS(NXY+2))+4.
            IF(N.EQ.1) GO TO 301
            IF(N.EQ.NXY) GO TO 302
            CALL SMOOT(XPAGE(N),YPAGE(N),-2)
            GO TO 303
```

```
17*        301 CALL SMOOT(XPAGE(N),YPAGE(N),0)
18*            GO TO 303
19*        302 CALL SMOOT(XPAGE(N),YPAGE(N),-24)
20*            GO TO 304
21*        303 N=N+1
22*            GO TO 300
23*        304 CALL PLOT(0.0,0.0,999)
24*         60 END

 OF COMPILATION:          NO  DIAGNOSTICS.

TCUR,.FTCUR
2/04/77-12:37:48 (,0)


 USED: CODE(1) 002656; DATA(0) 002615; BLANK COMMON(2) 000000


 OF COMPILATION:          NO  DIAGNOSTICS.


71-3 02/04/77 12:37:58
  IN TPF$.
  LIB MISD*PLOT.


MITS     001000 023250       3385 IBANK WORDS DECIMAL
         040000 065537      11104 DBANK WORDS DECIMAL
DDRESS   022324



   SEGMENT $MAIN$            001000 023250       040000 065537

-E2           $(1)     001000 001022
-E3           $(1)     001023 001106       $(2)      040000 040011
E2            $(1)     001107 001314       $(2)      040012 040031
IX            $(1)     001315 001445       $(2)      040032 040107
-E2           $(1)     001446 001730       $(2)      040110 040123
E2            $(1)     001731 001753
68            $(1)     001754 002175       $(2)      040124 040220
-E3           $(1)     002176 002433       $(2)      040221 040246
                                           $(2)      040247 042474
69            $(1)     002434 002460
-E3           $(1)     002461 002515
68            $(1)     002516 002551
68            $(1)     002552 002663
-E3           $(1)     002664 003061       $(2)      042475 042546
-E3           $(1)     003062 003356       $(2)      042547 042552
X             $(1)     003357 005072       $(2)      042553 042614
IX            $(1)     005073 005314       $(2)      042615 042764
IX            $(1)     005315 005551       $(2)      042765 042765
IX            $(1)     005552 007162       $(2)      042766 043021
E3            $(1)     007163 010045       $(2)      043022 043076
```

SHORT SERIES

INPUT

Card 1	I – Number of capillaries
	J – Capillary number
Card 2	NP – Number of pressures
	PRESS – Pressure levels, psi
Card 3	KOUNT – Number of volume-time data points
	VOL – Volume, cm^3
	T – Time, sec

OUTPUT

J – Capillary number

PRESS – Pressure, psi

SIGMA – Slope of volumetric rate curve

TAU – Shear stress, $dynes/cm^2$

D – Shear rate, sec^{-1}

VIS – Viscosity, poise

SAMPLE OUTPUT

CAPILLARY NUMBER	PRESSURE PSI	SLOPE CC/SEC	SHEAR STRESS DYNES/CM2	SHEAR RATE 1/SEC	VISCOSITY POISE
1	14.90	.001	2056.20	1388.19	1.4812
1	28.75	.002	3967.50	1950.00	2.0346
1	50.50	.003	6969.00	2941.72	2.3690
1	70.00	.004	9660.00	4420.00	2.1855
1	97.50	.006	13455.00	6474.00	2.0783
1	130.00	.008	17940.00	9234.04	1.9428
1	189.00	.012	26082.00	14129.14	1.8460
1	305.00	.019	42090.00	22285.72	1.8887
1	437.00	.028	60306.00	33294.86	1.8113
1	605.00	.038	83490.00	44905.72	1.8592
1	760.00	.049	104880.00	56761.72	1.8477
1	933.00	.060	128754.00	70356.00	1.8300
3	4.00	.001	668.00	268.00	2.4925
3	7.20	.002	1202.40	320.64	3.7500
3	13.70	.003	2287.90	674.79	3.3906
3	21.00	.005	3507.00	1048.07	3.3461
3	28.75	.007	4801.25	1424.23	3.3711
3	46.00	.012	7682.00	2498.14	3.0751
3	65.00	.019	10855.00	3820.91	2.8409
3	86.00	.027	14362.00	5388.71	2.6652
3	112.00	.037	18704.00	7504.00	2.4925
3	145.00	.051	24215.00	10194.86	2.3752
3	190.00	.069	31730.00	13818.75	2.2962
3	285.00	.107	47595.00	21523.01	2.2114
3	415.00	.157	69305.00	31487.12	2.2011
3	598.00	.231	99866.00	46513.46	2.1470
3	750.00	.306	125250.00	61492.37	2.0368
3	915.00	.380	152805.00	76380.00	2.0006
9	2.50	.003	523.75	110.76	4.7287
9	4.00	.004	838.00	159.04	5.2691
9	6.00	.006	1257.00	264.12	4.7592
9	9.00	.010	1885.50	428.84	4.3967
9	13.00	.017	2723.50	707.15	3.8513
9	19.00	.026	3980.50	1099.08	3.6217
9	24.50	.035	5132.75	1479.64	3.4689
9	29.00	.042	6075.50	1797.72	3.3796
9	46.00	.069	9637.00	2939.40	3.2786
9	60.00	.100	12570.00	4240.94	2.9640
9	80.00	.142	16760.00	6066.02	2.7629
9	115.00	.226	24092.50	9622.84	2.5037
9	132.00	.260	27654.00	11091.12	2.4933
9	154.00	.306	32263.00	13016.67	2.4786
9	182.00	.367	38129.00	15620.00	2.4410
9	250.00	.500	52375.00	21300.00	2.4589
5	.25	.009	138.50	21.59	6.4137
5	.38	.013	207.75	30.61	6.7868
5	.50	.019	277.00	42.81	6.4704
5	.75	.027	415.50	61.33	6.7745
5	1.00	.038	554.00	87.53	6.3294
5	1.50	.058	831.00	133.89	6.2065
5	2.00	.080	1108.00	183.91	6.0246
5	3.00	.130	1662.00	298.28	5.5719
5	4.50	.210	2493.00	482.07	5.1714
5	6.00	.307	3324.00	707.04	4.7013
5	8.00	.432	4432.00	994.27	4.4575

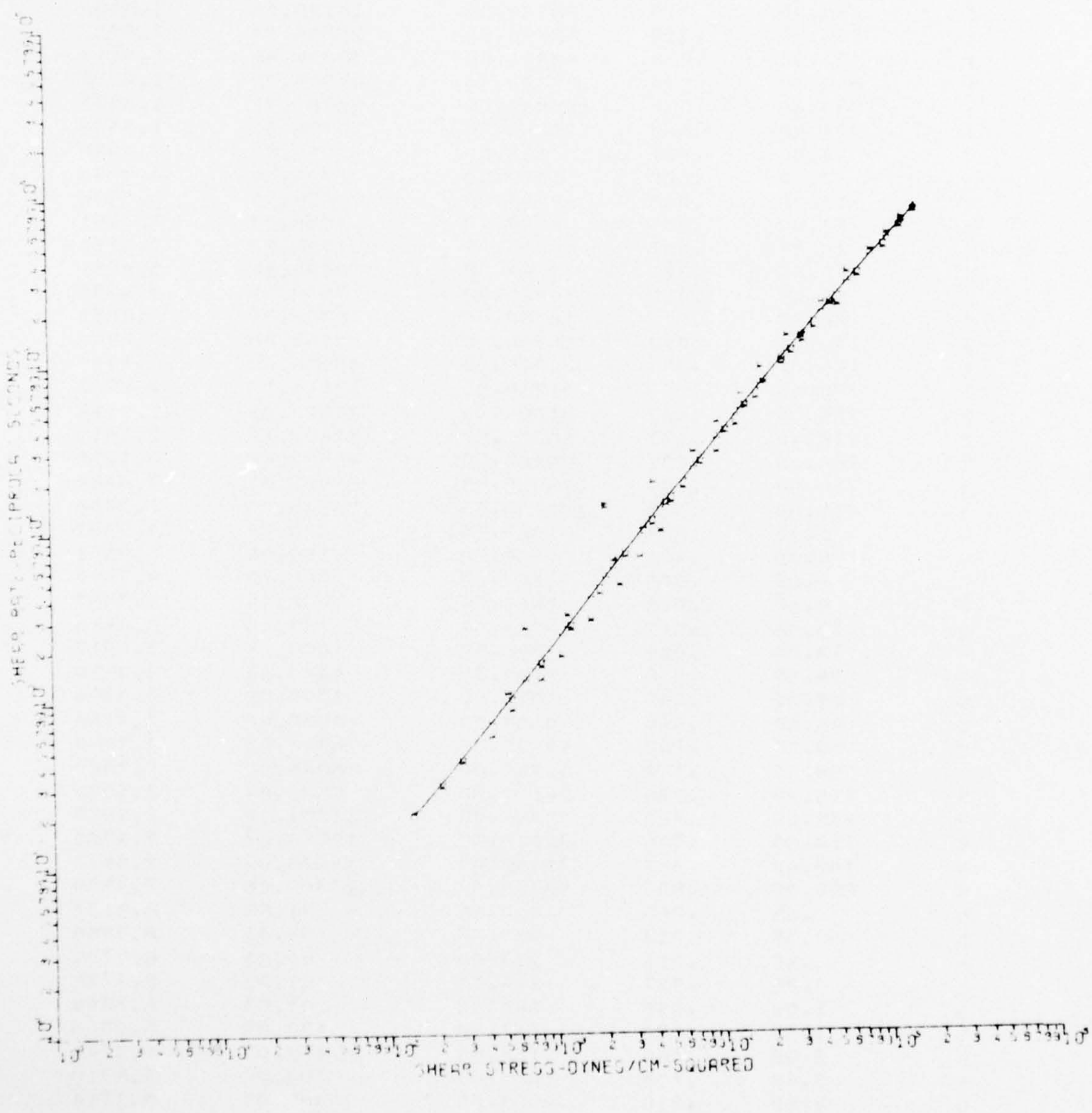


Figure A-1. Sample of Basic Flow Curve (Shear Rate Versus Shear Stress)

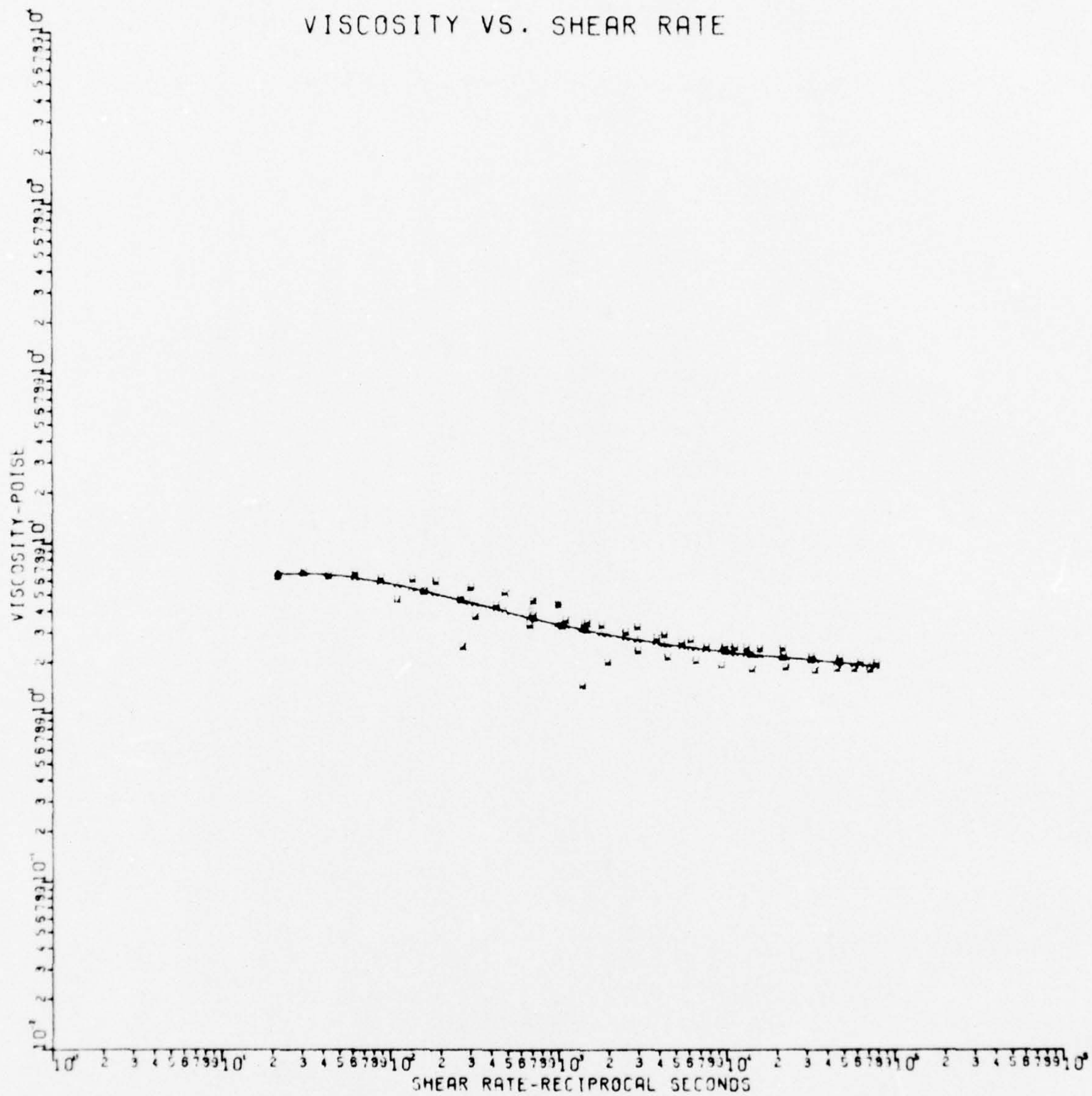
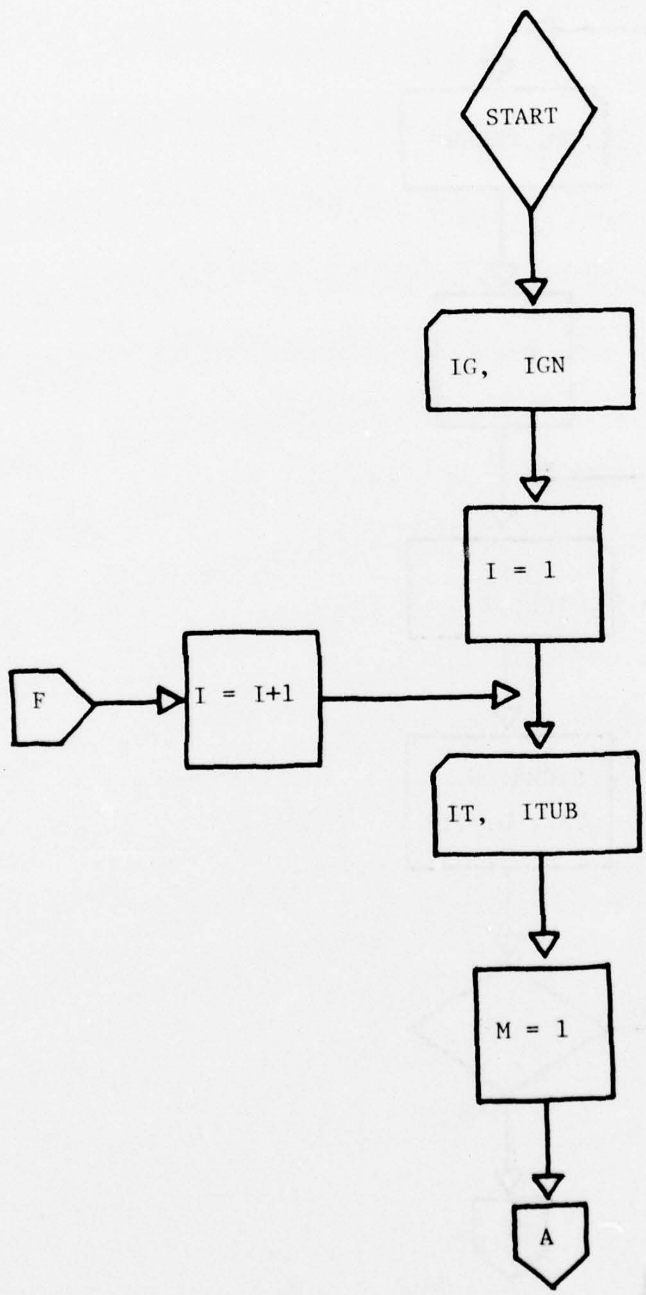
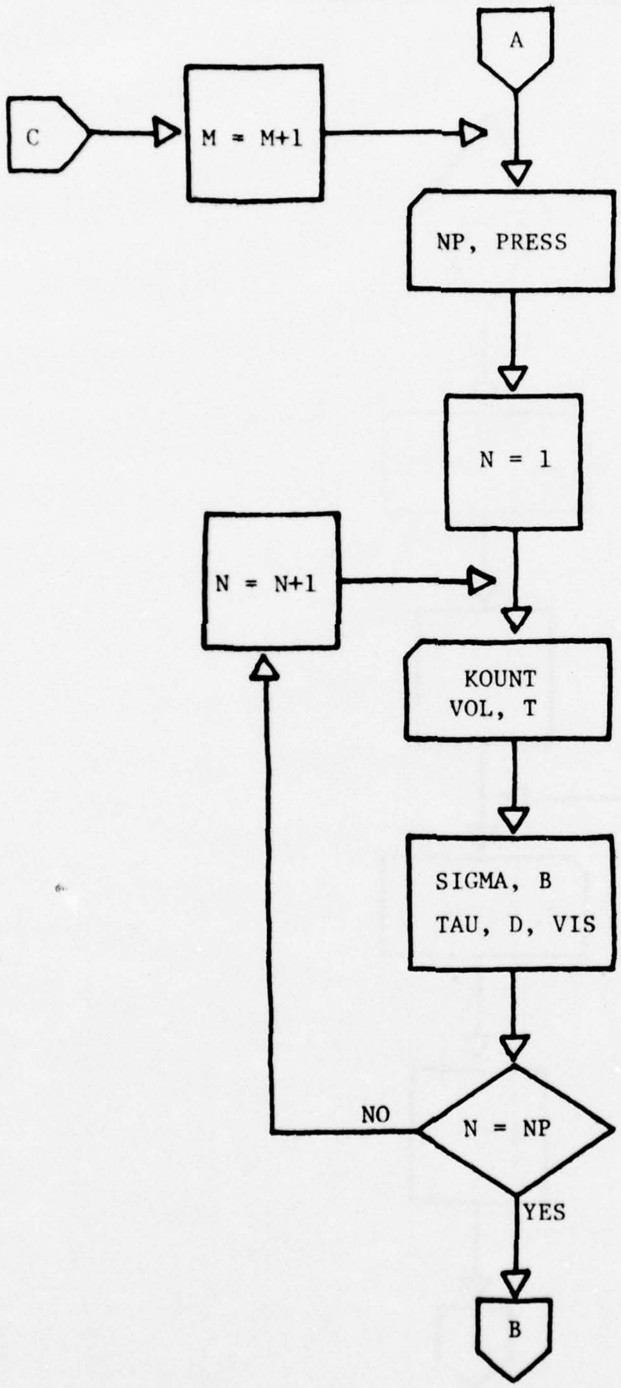


Figure A-2. Sample of Basic Flow Curve (Viscosity Versus Shear Rate)

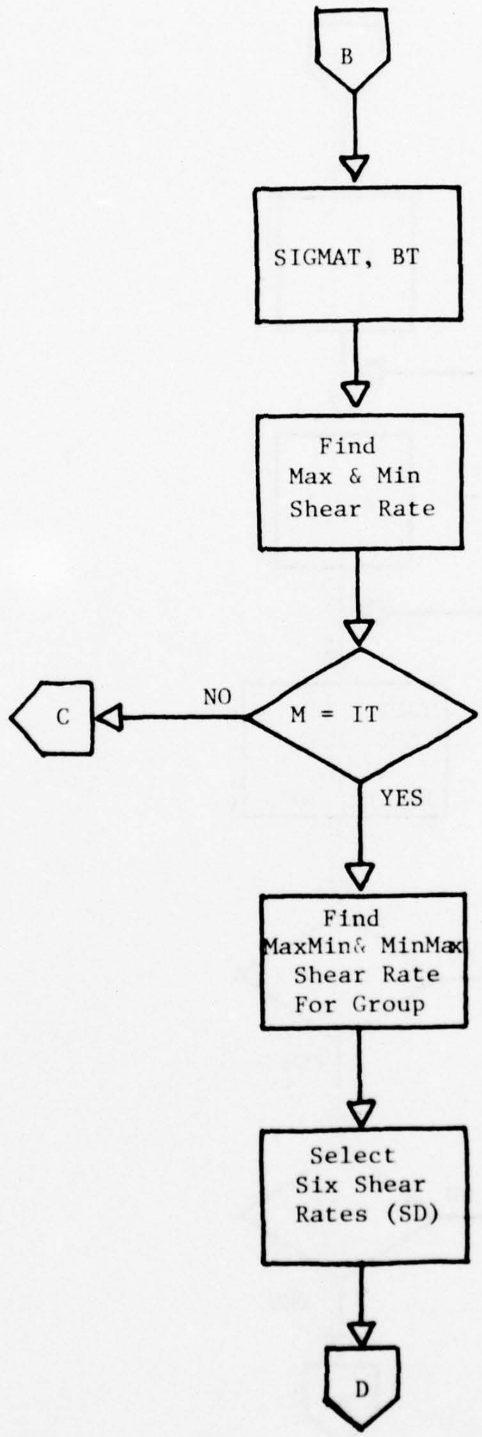
APPENDIX B

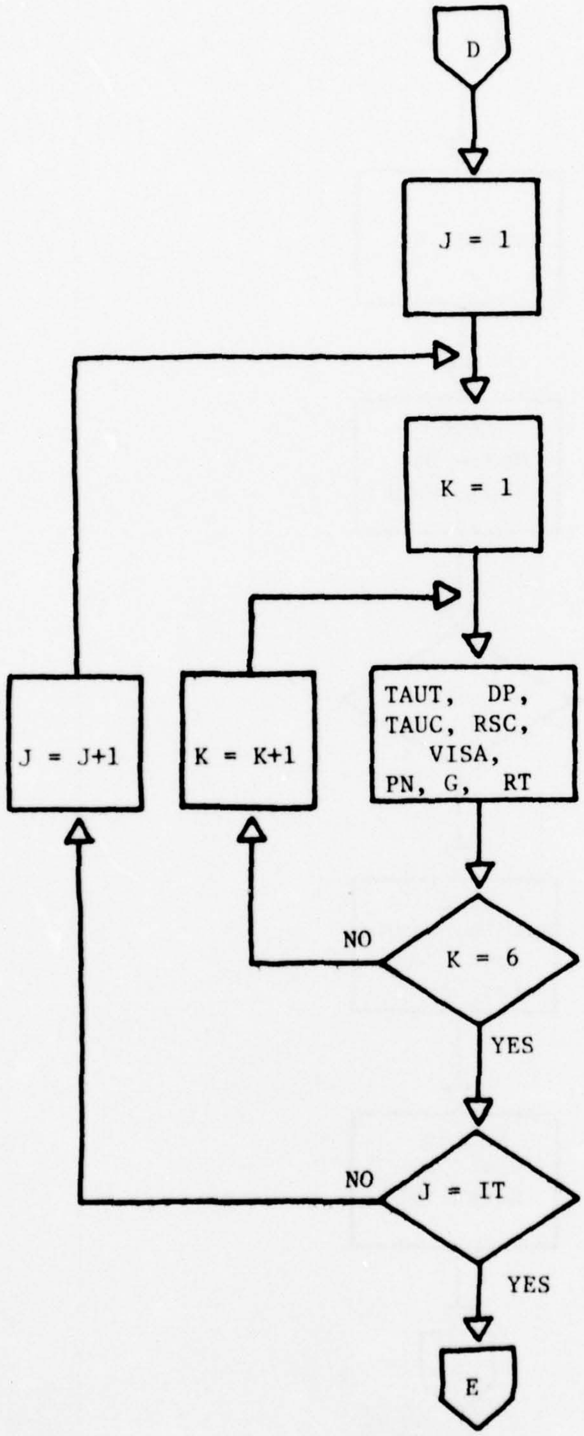
FLOW CHART FOR LONG-SERIES PHASE

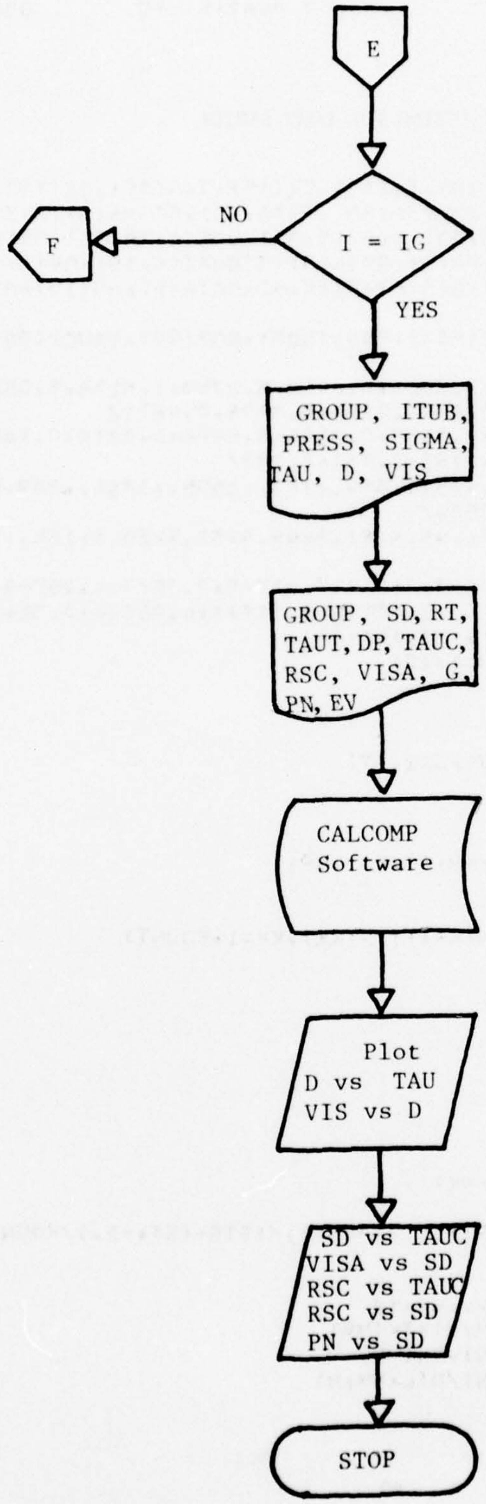




A
C
M = M+1
NP, PRESS
N = 1
N = N+1
KOUNT
VOL, T
SIGMA, B
TAU, D, VIS
NO
N = NP
YES
B


B
SIGMAT, BT
Find
Max & Min
Shear Rate
NO
C
M = IT
YES
Find
MaxMin& MinMax
Shear Rate
For Group
Select
Six Shear
Rates (SD)
D


D
J = 1
K = 1
TAUT, DP,
TAUC, RSC,
VISA,
PN, G, RT
J = J+1
K = K+1
NO
K = 6
YES
NO
J = IT
YES
E


E
NO
F
I = IG
YES
GROUP, ITUB, PRESS, SIGMA, TAU, D, VIS
GROUP, SD, RT, TAUT, DP, TAUC, RSC, VISA, G, PN, EV
CALCOMP Software
Plot
D vs TAU
VIS vs D
SD vs TAUC
VISA vs SD
RSC vs TAUC
RSC vs SD
PN vs SD
STOP

```
R 062412 TTKS        0000 R 062376 TV        0000 R 046715 VIS        0000 R 056007 VI
R 057502 VIS2        0000 R 006531 VOL
```

SAMPLE LISTING FOR LONG SERIES

```
      DIMENSION TAUT(6,15,6)
      DIMENSION GROUP(6),TL(15),TR(15),TK(15),TKS(15),DK(15),IGN(6),ITUB
     C(6,15),PRESS(6,15,30),VOL(30,50),T(30,50),SIGMA(6,15,30),B(6,15,30
     C),RS(6,15,30),TAU(6,15,30),D(6,15,30),VIS(6,15,30),DM(6,15),DMX(6)
     C,DN(6,15),DMN(6),R(6),PM(6),SD(6,6),SIGMAT(6,15),DP(6,15,6),TAUC(6
     C,6),RSC(6,6),VISA(6,6),G(6,6),RT(6,6),BC(6,6),NN(15),BT(6,15),NM(6
     C),PN(6,6),EV(6,6)
      DIMENSION D2(500),VIS2(500),TAU2(500),SD2(90),TAUC2(90),VISA2(90),
     CRSC2(90),PN2(90)
      DATA TL/2.5794,0.5959,3.8308,0.8428,5.0759,1.5138,5.0582,1.6515,5.
     C0853,1.1392,5.0851,0.0805,0.2182,0.3896,0.4671/
      DATA TR/0.0103,0.0103,0.0185,0.0185,0.0820,0.0310,0.161,0.082,0.03
     C1,0.161,0.26,0.0103,0.0185,0.031,0.082/
      DATA TK/138.,597.,167.,751.,554.,702.,1095.,1710.,209.5,4870.,1760
     C.,4410.,2920.,2740.,6050./
      DATA TKS/250.,57.9,207.,45.6,61.9,48.8,31.4,20.1,164.,7.08,19.6,7.
     C82,11.8,12.6,5.7/
      DATA DK/1.17E+6,1.17E+6,2.01E+5,2.01E+5,2.3E+3,4.26E+4,3.05E+2,2.3
     CE+3,4.26E+4,3.05E+2,72.2,1.17E+6,2.01E+5,4.26E+4,2.3E+3/
      DATA GROUP/'A','B','C','D','E','F'/
      READ(5,1) IG,(IGN(J),J=1,IG)
    1 FORMAT(   )
      I=1
   65 L=IGN(I)
      READ(5,2) IT,(ITUB(L,J),J=1,IT)
    2 FORMAT (   )
      M=1
    8 MM=ITUB(L,M)
      READ(5,3) NP,(PRESS(L,MM,K),K=1,NP)
    3 FORMAT(   )
      N=1
    6 READ(5,4) KOUNT,(VOL(N,KK),T(N,KK),KK=1,KOUNT)
    4 FORMAT(   )
      ST=0.
      STS=0.
      SV=0.
      STV=0.
      DO 10 NK=1,KOUNT
      ST=ST+T(N,NK)
      STS=STS+T(N,NK)**2.
      SV=SV+VOL(N,NK)
      STV=STV+T(N,NK)*VOL(N,NK)
   10 CONTINUE
      SIGMA(L,MM,N)=(STV-((ST*SV)/KOUNT))/(STS-(ST**2.)/KOUNT)
      TM=ST/KOUNT
      TV=SV/KOUNT
      B(L,MM,N)=TV-SIGMA(L,MM,N)*TM
      TAU(L,MM,N)=PRESS(L,MM,N)*TK(MM)
      D(L,MM,N)=SIGMA(L,MM,N)*DK(MM)
      VIS(L,MM,N)=TAU(L,MM,N)/D(L,MM,N)
```

```
      IF(N.EQ.NP) GO TO 5
      N=N+1
      GO TO 6
    5 NN(MM)=NP
      SS=0.
      STAU=0.
      STAUS=0.
      SDTAU=0.
      DO 21 NX=1,NP
      SS=SS+D(L,MM,NX)
      STAU=STAU+TAU(L,MM,NX)
      STAUS=STAUS+TAU(L,MM,NX)**2.
      SDTAU=SDTAU+D(L,MM,NX)*TAU(L,MM,NX)
   21 CONTINUE
      SIGMAT(L,MM)=(SDTAU-((SS*STAU)/NP))/(STAUS-(STAU**2.)/NP)
      TTAU=STAU/NP
      TD=SS/NP
      BT(L,MM)=TD-SIGMAT(L,MM)*TTAU
      DM(L,MM)=0.
      DO 20 J=1,NP
   20 IF(D(L,MM,J).GT.DM(L,MM)) DM(L,MM)=D(L,MM,J)
      DN(L,MM)=1000000.
      DO 22 J=1,NP
   22 IF(D(L,MM,J).LT.DN(L,MM)) DN(L,MM)=D(L,MM,J)
      IF(M.EQ.IT) GO TO 7
      M=M+1
      GO TO 8
    7 NM(L)=IT
      DMX(L)=1000000.
      DO 23 J=1,IT
      MM=ITUB(L,J)
   23 IF(DM(L,MM).LT.DMX(L)) DMX(L)=DM(L,MM)
      DMN(L)=0.
      DO 24 J=1,IT
      MM=ITUB(L,J)
   24 IF(DN(L,MM).GT.DMN(L)) DMN(L)=DN(L,MM)
      R(L)=DMX(L)-DMN(L)
      PM(L)=R(L)/2.
      SD(L,1)=DMN(L)
      SD(L,2)=DMN(L)+.2*R(L)
      SD(L,3)=DMN(L)+.4*R(L)
      SD(L,4)=DMN(L)+.6*R(L)
      SD(L,5)=DMN(L)+.8*R(L)
      SD(L,6)=DMX(L)
      DO 25 J=1,IT
      MM=ITUB(L,J)
      DO 26 K=1,6
      TAUT(L,MM,K)=(SD(L,K)-BT(L,MM))/SIGMAT(L,MM)
      DP(L,MM,K)=2.*TKS(MM)*TAUT(L,MM,K)
   26 CONTINUE
   25 CONTINUE
      K=1
   55 STKS=0.
      STKSS=0.
      SDP=0.
      STKSDP=0.
      DO 31 J=1,IT
```

```
      MM=ITUB(L,J)
      STKS=STKS+TKS(MM)
      STKSS=STKSS+TKS(MM)**2.
      SDP=SDP+DP(L,MM,K)
      STKSDP=STKSDP+TKS(MM)*DP(L,MM,K)
   31 CONTINUE
      TAUC(L,K)=((STKSDP-((STKS*SDP)/IT))/(STKSS-(STKS**2.)/IT))/2.
      TTKS=STKS/IT
      TDP=SDP/IT
      BC(L,K)=TDP-(TAUC(L,K)*TTKS)*2.
      RSC(L,K)=BC(L,K)/TAUC(L,K)
      VISA(L,K)=TAUC(L,K)/SD(L,K)
      PN(L,K)=TAUC(L,K)*RSC(L,K)
      G(L,K)=TAUC(L,K)/RSC(L,K)
      RT(L,K)=RSC(L,K)/SD(L,K)
      EV(L,K)=VISA(L,K)*(1.+RSC(L,K))
      IF(K.EQ.6) GO TO 50
      K=K+1
      GO TO 55
   50 IF(I.EQ.IG) GO TO 60
      I=I+1
      GO TO 65
   60 WRITE(6,100)
  100 FORMAT('1' '  GROUP   CAPILLARY   PRESSURE   SLOPE   SHEAR STRESS
     C  SHEAR RATE   VISCOSITY'/'            NUMBER         PSI        CC/SEC
     C    DYNES/CM2         1/SEC         POISE')
      NXY=1
      DO 70 I=1,IG
      L=IGN(I)
      IT=NM(L)
      DO 71 J=1,IT
      MM=ITUB(L,J)
      NP=NN(MM)
      DO 72 K=1,NP
      WRITE(6,101) GROUP(L),ITUB(L,J),PRESS(L,MM,K),SIGMA(L,MM,K),TAU(L,
     CMM,K),D(L,MM,K),VIS(L,MM,K)
  101 FORMAT(4X,A1,8X,I2,7X,F7.3,4X,F5.3,4X,F9.2,6X,F9.1,3X,F9.4)
      D2(NXY)=D(L,MM,K)
      TAU2(NXY)=TAU(L,MM,K)
      VIS2(NXY)=VIS(L,MM,K)
      NXY=NXY+1
   72 CONTINUE
   71 CONTINUE
   70 CONTINUE
      WRITE(6,102)
  102 FORMAT('1',' GROUP   SHEAR    TOTAL      APPLIED    CORRECTED   R
     CECOVERABLE   APPARENT    SHEAR    RELAXATION   NORMAL    EFFECTIVE
     C'/'           RATE     SHEAR      PRESSURE       SHEAR        SHEAR
     C     VISCOSITY   MODULUS      TIME          STRESS    VISCOSITY'/'
     C                  STRESS                    STRESS'/'           1/SEC
     C DYNES/CM2    DYNES/CM2    DYNES/CM2                     POISE    DYNES/
     CCM2  SECONDS     DYNES/CM2     POISE')
      NYZ=1
      DO 110 I=1,IG
      L=IGN(I)
      IT=NM(L)
      DO 111 J=1,IT
```

```
      MM=ITUB(L,J)
      DO 112 K=1,6
      WRITE(6,113) GROUP(L),SD(L,K),TAUT(L,MM,K),DP(L,MM,K),TAUC(L,K),RS
     CC(L,K),VISA(L,K),G(L,K),RT(L,K),PN(L,K),EV(L,K)
  113 FORMAT(4X,A1,2X,F9.2,2X,F9.1,3X,F9.0,3X,F9.2,4X,F9.2,2X,F9.4,1X,F9
     C.2,1X,F9.5,4X,F9.0,4X,F9.5)
      SD2(NYZ)=SD(L,K)
      TAUC2(NYZ)=TAUC(L,K)
      VISA2(NYZ)=VISA(L,K)
      RSC2(NYZ)=RSC(L,K)
      PN2(NYZ)=PN(L,K)
      NYZ=NYZ+1
  112 CONTINUE
  111 CONTINUE
  110 CONTINUE
      NXY=NXY-1
      CALL PLOTS(ID,ID,8)
      CALL PLOT(0.0,-36.0,-3)
      CALL PLOT(0.0,2.0,-3)
      CALL FACTOR(0.75)
      D2(NXY+1)=1.0
      D2(NXY+2)=.50
      TAU2(NXY+1)=1.0
      TAU2(NXY+2)=.50
      CALL LGAXS(0.0,0.0,29HSHEAR STRESS-DYNES/CM-SQUARED,-29,12.0,0.0,1
     C.0,.50)
      CALL LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,29,12.0,90.0,1
     C.0,.50)
      CALL LGLIN(TAU2,D2,NXY,1,-1,11,0)
      CALL SYMBOL(3.0,12.0,.21,27HSHEAR RATE VS. SHEAR STRESS,0.0,27)
      CALL PLOT(0.0,16.0,-3)
      VIS2(NXY+1)=.01
      VIS2(NXY+2)=.50
      CALL LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,-29,12.0,0.0,1
     C.0,.50)
      CALL LGAXS(0.0,0.0,15HVISCOSITY-POISE,15,12.0,90.0,.01,.50)
      CALL LGLIN(D2,VIS2,NXY,1,-1,11,0)
      CALL SYMBOL(3.0,12.0,.21,24HVISCOSITY VS. SHEAR RATE,0.0,24)
      NYZ=NYZ-1
      WRITE(6,500) NYZ
  500 FORMAT(///2X,'NYZ = ',I3)
      CALL PLOT(15.0,-16.0,-3)
      TAUC2(NYZ+1)=1.0
      TAUC2(NYZ+2)=1.0
      SD2(NYZ+1)=10.0
      SD2(NYZ+2)=1.0
      CALL LGAXS(0.0,0.0,29HSHEAR STRESS-DYNES/CM-SQUARED,-29,6.0,0.0,1.
     C0,1.0)
      CALL LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,29,6.0,90.0,10
     C.0,1.0)
      CALL LGLIN(TAUC2,SD2,NYZ,1,-1,11,0)
      CALL SYMBOL(1.0,6.0,.14,37HSHEAR RATE VS. CORRECTED SHEAR STRESS,0
     C.0,37)
      CALL SYMBOL(1.5,5.6,.07,39HINVERSE SLOPE EQUALS APPARENT VISCOSITY
     C,0.0,39)
      CALL PLOT(0.0,8.0,-3)
      VISA2(NYZ+1)=.001
```

```
      VISA2(NYZ+2)=1.0
      CALL LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,-29,6.0,0.0,10
     C.0,1.0)
      CALL LGAXS(0.0,0.0,15HVISCOSITY-POISE,15,6.0,90.0,.001,1.0)
      CALL LGLIN(SD2,VISA2,NYZ,1,-1,11,0)
      CALL SYMBOL(1.0,6.0,.14,33HAPPARENT VISCOSITY VS. SHEAR RATE,0.0,3
     C3)
      CALL PLOT(0.0,8.0,-3)
      RSC2(NYZ+1)=.10
      RSC2(NYZ+2)=1.0
      CALL LGAXS(0.0,0.0,29HSHEAR STRESS-DYNES/CM-SQUARED,-29,6.0,0.0,1.
     C0,1.0)
      CALL LGAXS(0.0,0.0,17HRECOVERABLE SHEAR,17,6.0,90.0,.10,1.0)
      CALL LGLIN(TAUC2,RSC2,NYZ,1,-1,11,0)
      CALL SYMBOL(1.0,6.0,.14,34HRECOVERABLE SHEAR VS. SHEAR STRESS,0.0,
     C34)
      CALL SYMBOL(1.5,5.6,.07,34HINVERSE SLOPE EQUALS SHEAR MODULUS,0.0,
     C34)
      CALL PLOT(0.0,8.0,-3)
      CALL LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,-29,6.0,0.0,10
     C.0,1.0)
      CALL LGAXS(0.0,0.0,17HRECOVERABLE SHEAR,17,6.0,90.0,.10,1.0)
      CALL LGLIN(SD2,RSC2,NYZ,1,-1,11,0)
      CALL SYMBOL(1.0,6.0,.14,32HRECOVERABLE SHEAR VS. SHEAR RATE,0.0,32
     C)
      CALL SYMBOL(1.5,5.6,.07,28HSLOPE EQUALS RELAXATION TIME,0.0,28)
      CALL PLOT(10.0,-24.0,-3)
      PN2(NYZ+1)=10.0
      PN2(NYZ+2)=1.0
      CALL LGAXS(0.0,0.0,29HSHEAR RATE-RECIPROCAL SECONDS,-29,6.0,0.0,10
     C.0,1.0)
      CALL LGAXS(0.0,0.0,30HNORMAL STRESS-DYNES/CM-SQUARED,30,6.0,90.0,1
     C0.0,1.0)
      CALL LGLIN(SD2,PN2,NYZ,1,-1,11,0)
      CALL SYMBOL(1.0,6.0,.14,28HNORMAL STRESS VS. SHEAR RATE,0.0,28)
      CALL PLOT(0.0,0.0,999)
      END

D OF COMPILATION:          NO  DIAGNOSTICS.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LONG SERIES

INPUT

Card 1	IG – Number of groups
	IGN – Group number
Card 2	IT – Number of tubes for each group
	ITUB – Tube number
Card 3	NP – Number of pressure for each tube
	PRESS – Pressure levels
Card 4	KOUNT – Number of volume-time pairs
	VOL – Volumes
	T – Time

OUTPUT

Table 1	GROUP – Group name
	ITUB – Tube number
	PRESS – Pressure level, psi
	SIGMA – Slope of volume-time curves
	TAU – Shear stress, dynes/cm^2
	D – Shear rate, sec^{-1}
	VIS – Viscosity, poise
Table 2	GROUP – Group name
	SD – Selected shear rate, sec^{-1}
	TAUT – Total shear stress, dynes/cm^2
	DP – Applied pressure, dynes/cm^2
	TAUC – Corrected shear stress, dynes/cm^2

OUTPUT

RSC – Recoverable shear

VISA – Apparent viscosity, poise

G – Shear modulus, dynes/cm^2

RT – Relaxation time, seconds

PN – Normal stress, dynes/cm^2

EV – Effective viscosity, poise

SAMPLE OUTPUT

GROUP	CAPILLARY NUMBER	PRESSURE PSI	SLOPE CC/SEC	SHEAR STRESS DYNES/CM2	SHEAR RATE 1/SEC	VISCOSITY POISE
F	1	12.000	.004	1656.00	5237.1	.3162
F	1	20.000	.007	2760.00	7800.0	.3538
F	1	30.000	.008	4140.00	9438.0	.4387
F	1	50.000	.012	6900.00	14040.0	.4915
F	1	80.000	.022	11040.00	25316.6	.4361
F	1	120.000	.034	16560.00	40357.1	.4105
F	1	163.000	.048	22494.00	56382.9	.3990
F	1	205.000	.063	28290.00	74100.0	.3818
F	1	250.000	.082	34500.00	95963.3	.3594
F	1	300.000	.092	41400.00	107533.2	.3850
F	1	400.000	.153	55200.00	178515.5	.3092
F	1	500.000	.224	69000.00	261940.3	.2634
F	1	600.000	.321	82800.00	375766.4	.2203
F	1	700.000	.459	96600.00	536752.6	.1800
F	2	2.000	.003	1194.00	3744.0	.3189
F	2	5.000	.007	2985.00	7722.0	.3866
F	2	9.000	.009	5373.00	10563.4	.5086
F	2	12.000	.011	7164.00	12636.0	.5670
F	2	20.000	.016	11940.00	18742.3	.6371
F	2	30.000	.022	17910.00	25896.0	.6916
F	2	50.000	.033	29850.00	39000.0	.7654
F	2	70.000	.050	41790.00	58032.0	.7201
F	2	90.000	.075	53730.00	87248.6	.6158
F	2	122.000	.096	72834.00	112786.0	.6458
F	2	151.000	.147	90147.00	172261.6	.5233
F	2	220.000	.243	131340.00	284594.6	.4615
F	2	300.000	.333	179100.00	390000.0	.4592
F	2	400.000	.511	238800.00	598295.4	.3991
F	12	1.000	.004	4410.00	4498.0	.9804
F	12	2.000	.005	8820.00	5961.4	1.4795
F	12	5.000	.007	22050.00	8112.0	2.7182
F	12	10.000	.010	44100.00	11727.9	3.7603
F	12	20.000	.017	88200.00	19812.0	4.4518
F	12	36.000	.026	158760.00	30447.9	5.2142
F	12	50.000	.040	220500.00	46644.0	4.7273
F	12	80.000	.073	352800.00	85566.0	4.1231
F	12	122.000	.144	538020.00	167951.6	3.2034
F	12	164.000	.183	723240.00	214024.4	3.3792
F	12	230.000	.335	*********	391406.2	2.5910
F	12	300.000	.459	*********	536752.6	2.4648

SAMPLE OUTPUT (continued)

GROUP	SHEAR RATE	TOTAL SHEAR STRESS	APPLIED PRESSURE	CORRECTED SHEAR STRESS	RECOVERABLE SHEAR	APPARENT VISCOSITY	SHEAR MODULUS	RELAXATION TIME	NORMAL STRESS	EFFECTIVE VISCOSITY
	1/SEC	DYNES/CM2	DYNES/CM2	DYNES/CM2		POISE	DYNES/CM2	SECONDS	DYNES/CM2	POISE
D	3408.00	2184.0	716357.	2130.70	14.52	.6252	146.71	.00426	30946.	9.70552
D	7933.07	5422.2	1778472.	4497.09	70.50	.5669	63.79	.00889	317041.	40.53135
D	12458.13	8660.3	2840586.	6863.47	87.88	.5509	78.10	.00705	603136.	48.96305
D	16983.20	11898.5	3902701.	9229.85	96.34	.5435	95.80	.00567	889231.	52.90203
D	21508.27	15136.6	4964816.	11596.24	101.35	.5392	114.41	.00471	1175326.	55.18448
D	26033.33	18374.8	6026930.	13962.62	104.67	.5363	133.40	.00402	1461421.	56.67288
D	3408.00	3024.5	295193.	2130.70	14.52	.6252	146.71	.00426	30946.	9.70552
D	7933.07	8328.8	812892.	4497.09	70.50	.5669	63.79	.00889	317041.	40.53135
D	12458.13	13633.1	1330591.	6863.47	87.88	.5509	78.10	.00705	603136.	48.96305
D	16983.20	18937.4	1848290.	9229.85	96.34	.5435	95.80	.00567	889231.	52.90203
D	21508.27	24241.7	2365989.	11596.24	101.35	.5392	114.41	.00471	1175326.	55.18448
D	26033.33	29546.0	2883688.	13962.62	104.67	.5363	133.40	.00402	1461421.	56.67288
D	3408.00	1659.0	41808.	2130.70	14.52	.6252	146.71	.00426	30946.	9.70552
D	7933.07	15358.9	387045.	4497.09	70.50	.5669	63.79	.00889	317041.	40.53135
D	12458.13	29058.8	732283.	6863.47	87.88	.5509	78.10	.00705	603136.	48.96305
D	16983.20	42758.7	1077520.	9229.85	96.34	.5435	95.80	.00567	889231.	52.90203
D	21508.27	56458.6	1422757.	11596.24	101.35	.5392	114.41	.00471	1175326.	55.18448
D	26033.33	70158.5	1767995.	13962.62	104.67	.5363	133.40	.00402	1461421.	56.67288
E	6619.60	4182.2	1731413.	3920.33	12.26	.5922	319.70	.00185	48074.	7.85454
E	26483.45	14419.8	5969782.	10651.80	145.57	.4022	73.18	.00550	1550536.	58.94058
E	46347.29	24657.4	10208151.	17383.27	175.63	.3751	98.98	.00379	3052999.	66.24728
E	66211.13	34895.0	14446519.	24114.74	188.91	.3642	127.65	.00285	4555461.	69.16625
E	86074.98	45132.6	18684888.	30846.20	196.39	.3584	157.07	.00228	6057924.	70.73708
E	105938.83	55370.2	22923257.	37577.67	201.19	.3547	186.77	.00190	7560386.	71.72030
E	6619.60	627.7	57243.	3920.33	12.26	.5922	319.70	.00185	48074.	7.85454
E	26483.45	27058.0	2467694.	10651.80	145.57	.4022	73.18	.00550	1550536.	58.94058
E	46347.29	53488.4	4878144.	17383.27	175.63	.3751	98.98	.00379	3052999.	66.24728
E	66211.13	79918.8	7288595.	24114.74	188.91	.3642	127.65	.00285	4555461.	69.16625
E	86074.98	106349.2	9699046.	30846.20	196.39	.3584	157.07	.00228	6057924.	70.73708
E	105938.83	132779.6	12109496.	37577.67	201.19	.3547	186.77	.00190	7560386.	71.72030
E	6619.60	18162.6	428637.	3920.33	12.26	.5922	319.70	.00185	48074.	7.85454
E	26483.45	78254.5	1846805.	10651.80	145.57	.4022	73.18	.00550	1550536.	58.94058
E	46347.29	138346.3	3264973.	17383.27	175.63	.3751	98.98	.00379	3052999.	66.24728
E	66211.13	198438.2	4683142.	24114.74	188.91	.3642	127.65	.00285	4555461.	69.16625
E	86074.98	258530.1	6101310.	30846.20	196.39	.3584	157.07	.00228	6057924.	70.73708
E	105938.83	318622.0	7519478.	37577.67	201.19	.3547	186.77	.00190	7560386.	71.72030
F	5237.14	9014.4	4507177.	7543.56	90.11	1.4404	83.72	.01721	670750.	131.23447
F	111540.23	30521.2	15260603.	21322.36	210.47	.1912	101.31	.00189	4487720.	40.42526
F	217843.32	52028.1	26014029.	35101.15	236.34	.1611	148.52	.00108	8205691.	38.24213
F	324146.41	73534.9	36767455.	48879.95	247.62	.1508	197.40	.00076	12103661.	37.49000
F	430449.49	95041.8	47520881.	62658.74	253.94	.1456	246.75	.00059	15911631.	37.11072
F	536752.59	116548.6	58274308.	76437.54	257.98	.1424	296.29	.00048	19719603.	36.88113
F	5237.14	11089.8	1284194.	7543.56	90.11	1.4404	83.72	.01721	670750.	131.23447
F	111540.23	55411.6	6416660.	21322.36	210.47	.1912	101.31	.00189	4487720.	40.42526
F	217843.32	99733.4	11549126.	35101.15	236.34	.1611	148.52	.00108	8205691.	38.24213
F	324146.41	144055.2	16681592.	48879.95	247.62	.1508	197.40	.00076	12103661.	37.49000
F	430449.49	188377.0	21814058.	62658.74	253.94	.1456	246.75	.00059	15911631.	37.11072
F	536752.59	232698.8	26946524.	76437.54	257.98	.1424	296.29	.00048	19719603.	36.88113
F	5237.14	64653.8	1011185.	7543.56	90.11	1.4404	83.72	.01721	670750.	131.23447
F	111540.23	335657.7	5249687.	21322.36	210.47	.1912	101.31	.00189	4487720.	40.42526
F	217843.32	606661.7	9488189.	35101.15	236.34	.1611	148.52	.00108	8205691.	38.24213
F	324146.41	877665.6	13726690.	48879.95	247.62	.1508	197.40	.00076	12103661.	37.49000
F	430449.49	1148669.5	17965191.	62658.74	253.94	.1456	246.75	.00059	15911631.	37.11072

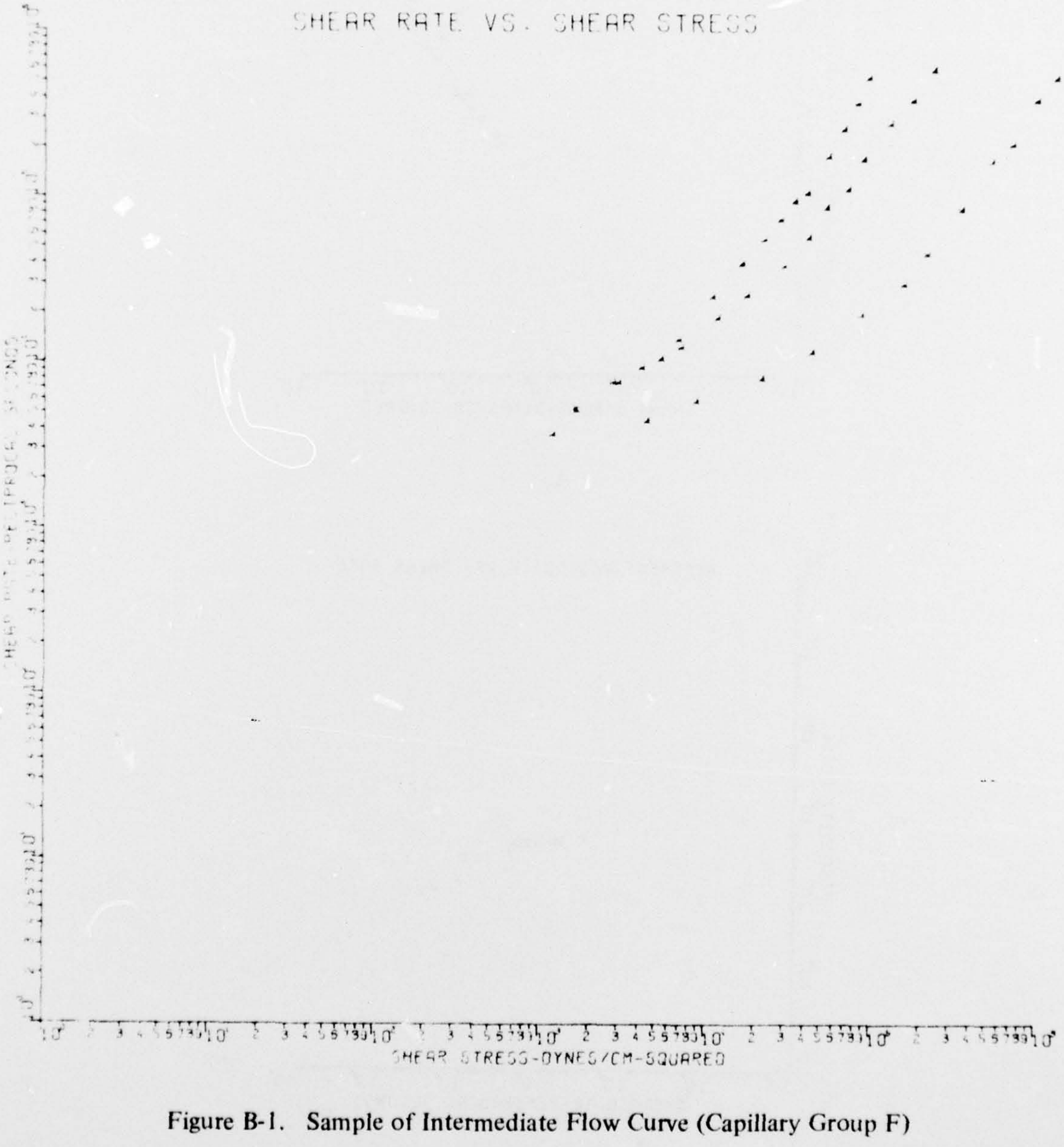

Figure B-1. Sample of Intermediate Flow Curve (Capillary Group F)

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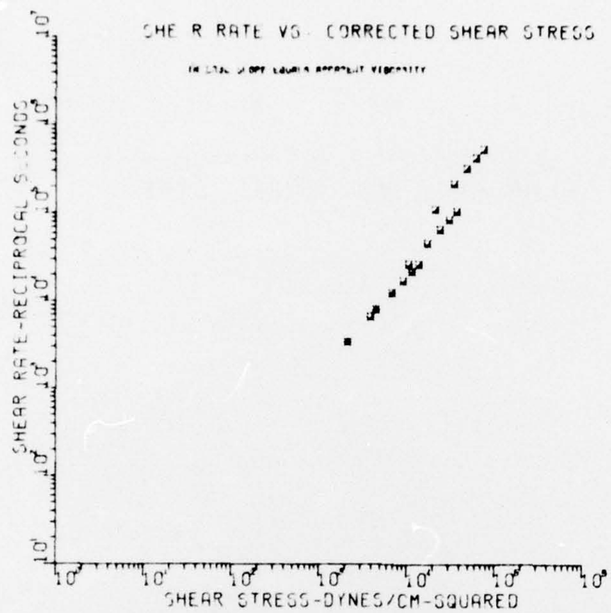
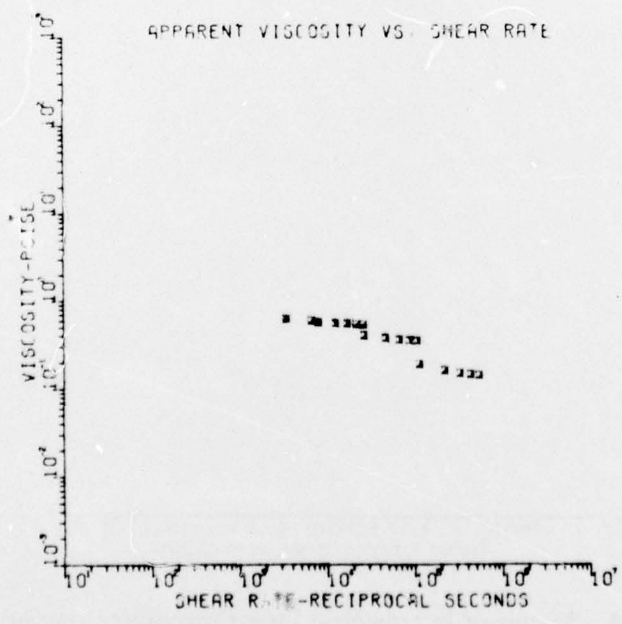
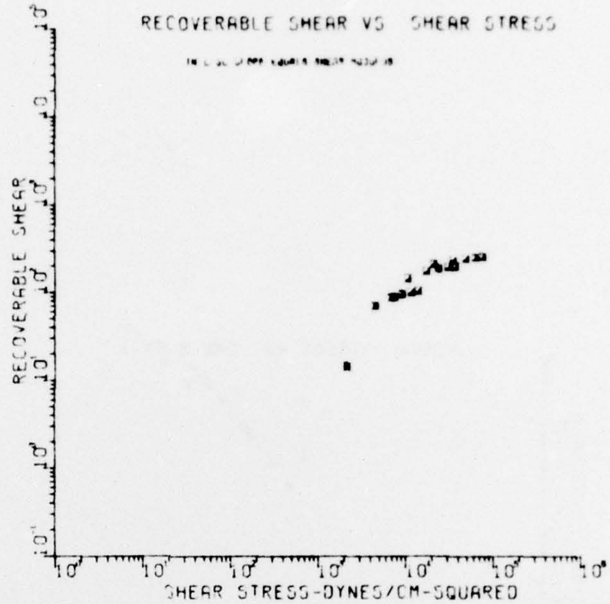


A



B

Figure B-2. Sample of Flow Curves Characterizing the Properties of a Viscoelastic Fluid Using All of the Capillary Groups



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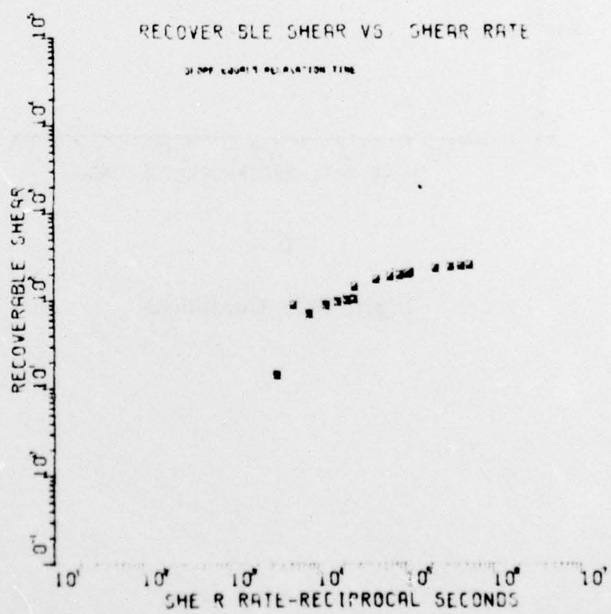
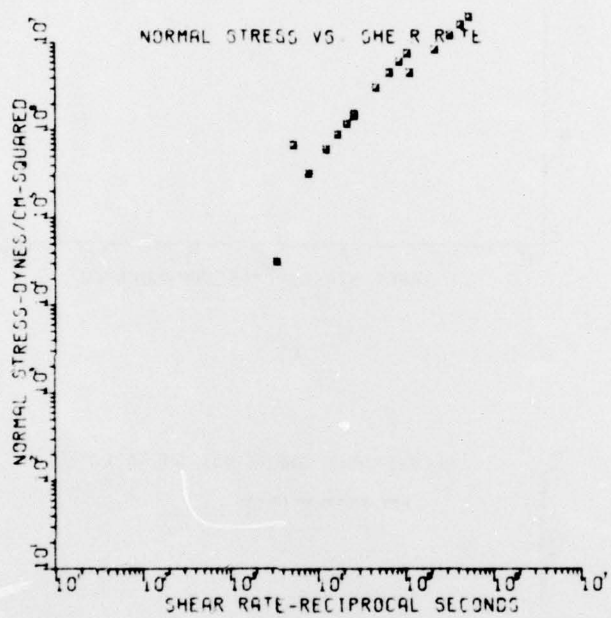


D

Figure B-2. Continued



E

Figure B-2. Continued

APPENDIX C

PROCEDURE FOR THE HIGH-PRESSURE CAPILLARY VISCOMETER EXPERIMENT EVALUATION

I. Construct deformation–recoil curve:

a. Plot Δ volume versus time rectilinearly for each applied pressure ΔP.

b. Graphically determine the slope of volume versus Δ time.

c. Calculate the shear rate, shear stress, and apparent viscosity.

II. Construct consistency curve:

a. Plot log shear rate versus log shear stress for each group.

b. For selected isoshear rates graphically determine total shear stresses.

c. Calculate the total applied pressure for the associated total shear stress.

III. Construct pressure–dimension curve:

a. Plot total applied pressure versus ℓ/r ratio for each tube by groups.

b. Graphically determine the corrected shear stress (equals the slope of each curve divided by two) and the recoverable shear (equals the X-intercept value multiplied by a negative two).

IV. Construct curves of generalized viscoelastic functional parameters:

a. Plot the log of the selected shear rates versus the log of the corrected shear stress for all of the groups. The inverse slope equals the apparent viscosity.

b. Plot log apparent viscosity versus the log of the selected shear rates for all groups.

c. Plot log recoverable shear versus the log of the corrected shear stress for each group. The inverse slope equals the shear modulus.

d. Plot log recoverable shear versus log shear rate for each group. The slope equals the relaxation time.

e. Plot log normal stress versus the log of the selected shear rate for each group.

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